3.4 Recycler Electron Cooling

A complete description of the electron cooling project can be found in Reference [31]. Here we provide a discussion of the essential elements emphasizing the integration of the project into the overall plans for Run IIb.

3.4.1 Background

The Laboratory started in 1995 to investigate the application of electron cooling to 8.9 GeV/c antiprotons in the Recycler as a promising component of an upgrade of Tevatron luminosity beyond the Run IIa goals. The idea was not entirely new at that time; it had been proposed as an upgrade path for the Accumulator as early as 1985,[29] and there had been some experimental work as well as conceptual development.[30] The practice and principles are well established for ions with kinetic energy of less than 500 MeV/nucleon. For ions of higher energy the fundamentals are the same, but hardware development is required and the technical problems differ. Technical details about the Fermilab R&D program can be found in Ref. [31]. To date, electron cooling at relativistic energies remains an unproven technology, and thus constitutes a high-risk segment of the Run2b upgrades plan. Fermilab is currently the only laboratory pursuing the high-energy electron cooling R&D at full scale; conceptual and experimental studies for similar systems are being carried on at Budker INP (Russia), BNL (USA), DESY (Germany), and GSI (Germany).

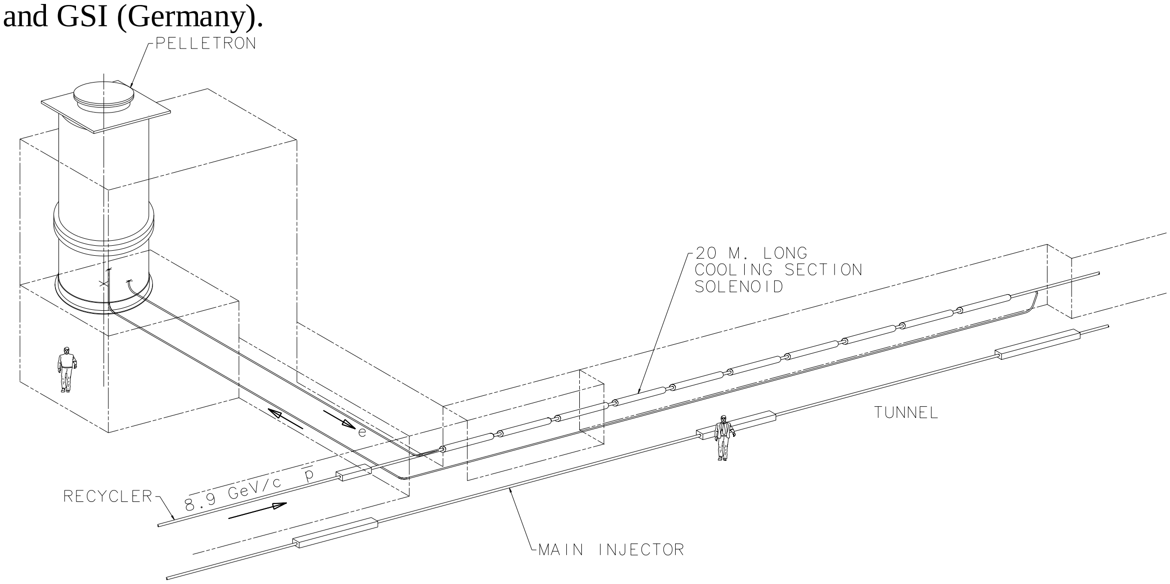

Figure 3.4.1 *Schematic layout of the Recycler electron cooling system.*

The Recycler currently employs a stochastic cooling system to collect multiple batches from the Accumulator. Electron cooling will improve cooling performance in the Recycler, permitting to have faster stacking and larger stacks, and ultimately to re-cool (recycle) antiprotons, which remain at the end of Tevatron stores. In combination with other accelerator upgrades it will permit substantially greater luminosity in the collider.

The Recycler electron cooler, discussed here, will be installed in the MI-30 section of the Recycler tunnel and it is schematically shown in Figure 3.4.1.

A charged particle (i.e. an antiproton) traveling in an electron beam undergoes Coulomb scattering with the electrons. The resulting friction and velocity diffusion tend to bring such particles into thermal equilibrium with the electrons. If the particle kinetic energy in the beam frame is high in the comparison with the electron temperature, diffusion is insignificant and the particles are cooled. The method of electron cooling was originally suggested by A. M. Budker.[32] It was developed and studied then both theoretically and experimentally. An ample list of the references can be found in Ref. [33].

3.4.2 Potential and goals

Electron cooling can reduce the spread in all three components of beam momentum simultaneously. Its primary advantage over stochastic cooling is that the cooling effect is practically independent of antiproton beam intensity up to the Recycler stack sizes of about 2×10^{13} antiprotons. Its greatest disadvantage is that the effect is very weak until the antiproton emittances are already close to the values wanted in the collider. Thus, the two processes can be seen as complementary rather than competitive. Electron cooling will prove very powerful in the Recycler as an add-on to the stochastic pre-cooling in the Antiproton Source and Recycler.

The ultimate goal is to realize a luminosity of $0.5\text{-}1.0\times10^{33}$ $cm^{-2}s^{-1}$ in the Tevatron collider by supplying a larger flux of antiprotons. The conceptual design studies[34] demonstrate that this can be accomplished by providing longitudinal emittance cooling rates in the Recycler of 200 eV·s/h or higher (in conjunction with the transverse stochastic cooling). The specific technical goal for the Recycler with the electron cooling system is to deliver 1.1×10^{13} antiprotons with a 150 eV-s longitudinal phase-space area (98%) and 10 π-mm-mrad transverse emittance (95%, norm.) in 6-7 hours.

3.4.3 Recycler beam cooling overview

The purposes of the Recycler beam cooling system (stochastic or electron) are:

1. To re-cool the recycled beam during a time period of a collider store;
2. To aid beam stacking in the Recycler during frequent transfers from the Accumulator;
3. To counteract various beam heating mechanisms, such as residual-gas and intra-beam scattering.

For Run2a, the stochastic cooling system alone is thought to be adequate. An example of simulations for the transverse cooling is shown in Figure 3.4.2. The attainable emittance cooling rate is thought to be about 15 π mm-mrad/hour (normalized, 95%) for modest stack sizes. Electron cooling and stochastic cooling are complementary in principle, and, at least during the earliest operation of the electron cooling system, that complementarity will be exploited by using the stochastic cooling for the large transverse emittance of the recycled antiprotons whereas the electron cooling will be optimized for longitudinal cooling to increase the stacking rate and maximum stack current. At the time of writing this report the Recycler stochastic cooling system has not been tested yet.

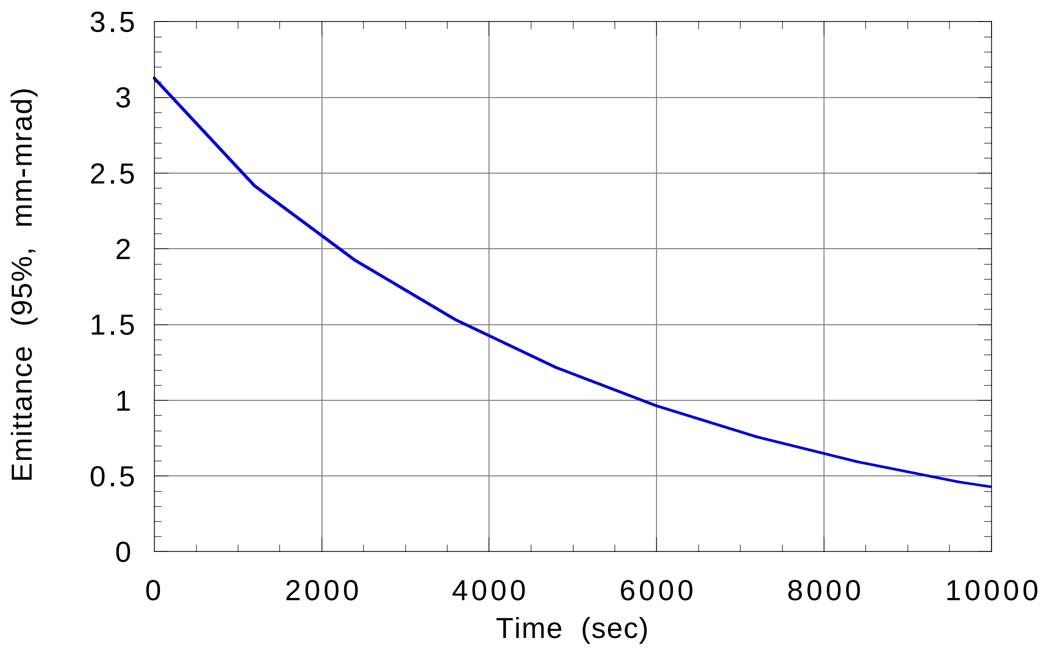

Figure 3.4.2 *Evolution of the (unnormalized) emittance of 5×10^{12} particles in the Recycler with the full momentum spread $\pm2\times10^{-3}$ during stochastic cooling with 2-4 GHz bandwidth.*

3.4.4 Cooling scenario simulations

A possible Run2b scenario for the periodic cooling-stacking process in the Recycler is as follows:

- t = 0: Up to 100 bunches of (hot) antiprotons leave the Tevatron, are decelerated in the Main Injector, and arrive at the Recycler, sharing its circumference with the already cooled antiproton beam. Then, the cold portion is transferred to the Main Injector, releasing the phase space for the hot beam with N=(2.5-10)$\times10^{12}$ antiprotons occupying A = 400 eVs of the longitudinal phase space and 30 π mm-mrad of the normalized, 95% emittance. Transverse stochastic pre-cooling begins.
- Every 15 minutes, a fresh antiproton batch arrives from the Accumulator. Its population is 10^{11} in 10 eVs and 15 π mm-mrad (normalized, 95%). It is merged longitudinally with the Recycler stack by means of a barrier-bucket technique.[35]
- t = 1-2 hours: Stochastic pre-cooling of the recycled antiprotons ends; beam emittance is now 15 π mm-mrad. Electron cooling begins.
- t = 5-8 hours: Electron cooling ends producing a beam with a 10-π emittance and 150 eVs or less longitudinal phase-space area. The cycle is then repeated.

To simulate the electron cooling process, a multi-particle computer code has been written. This code tracks the time evolution of an ensemble of cooled particles, optimizes the cooling process under various conditions and finds the tolerances for imperfections. The simulated evolution of the recycled antiprotons from the initial state is shown in

Figure 3.4.3 and Figure 3.4.4 in terms of the distribution integral as a function of the particle's betatron action and its momentum offset.

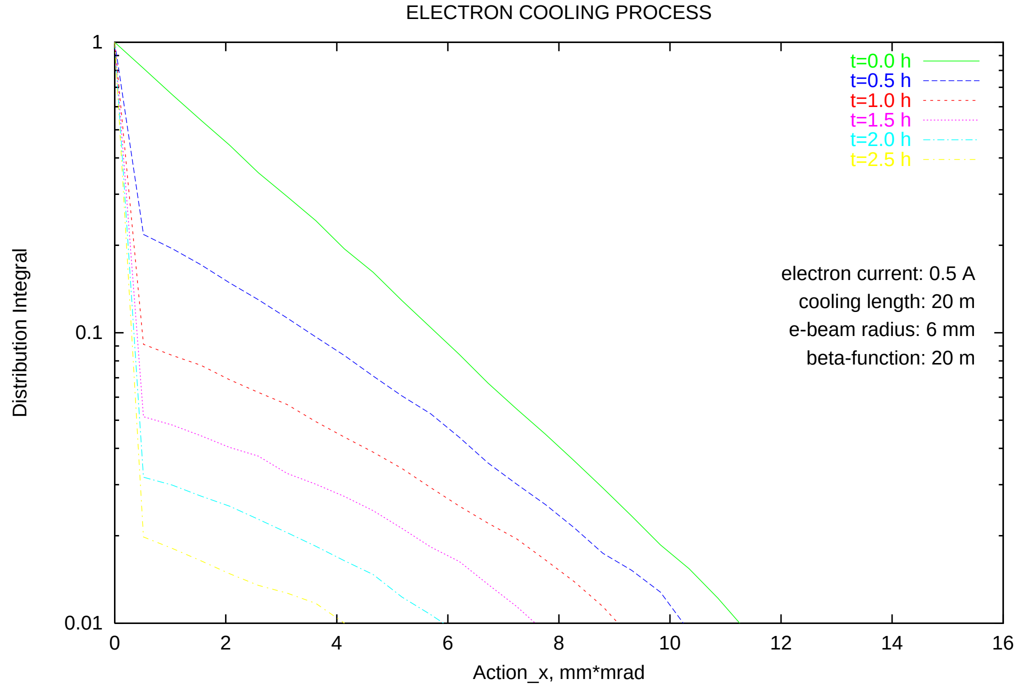

Figure 3.4.3 *Evolution of the transverse beam distribution during electron cooling. Initial distribution: gaussian with a 15 π mm-mrad (n, 95%) emittance. The initial cooling rate for a 15 π mm-mrad beam: 6 π mm-mrad/hr.*

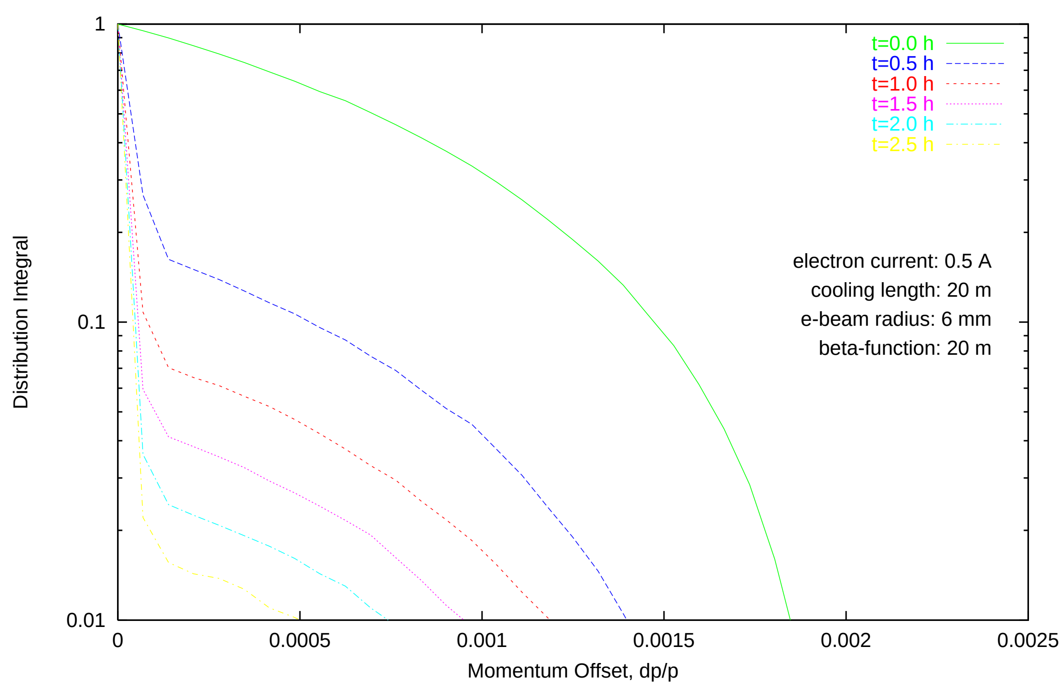

Figure 3.4.4 *Evolution of the momentum distribution. The initial distribution: parabolic.*

Electron cooling tends to shape a narrow core of super-cooled particles. The above figures show this core as a narrow peak at the origin. The actual size of this core is determined by equilibrium between cooling and the intra-beam scattering diffusion rate and is estimated elsewhere.[34]

The conclusion from the simulations is that the transverse cooling of the recycled antiprotons from ε = 15 π mm-mrad to ε = 10 π mm-mrad requires 0.9 Ampere×hour (Ah) of (electron beam current)×(cooling time), for a 20-m long cooling section. For batches from the Accumulator, this value is 0.5 Ah.

The longitudinal phase space area, A, shrinks with a rate $r_0 \approx 1.2$ A^{-1}h^{-1} over the whole interesting interval 150 eVs < A < 400 eVs. This approximate rate is used in the stacking model discussed below.

The longitudinal phase-space evolution of the cooling-stacking process can be described as

$$\dot{A} = -r_0 A + f_S A_b + f_S \Delta_S A \ , \tag{3.4.1}$$

where f_S is the stacking rate (the number of injections per hour), A_b is the Accumulator batch phase-space area, and Δ_S is the fractional phase-space area dilution because of the stacking imperfections. The solution of this equation is

$$A(t) = A(\infty) + (A(0) - A(\infty)) \times \exp(-[r_0 - f_S \Delta_S]t) , \tag{3.4.2}$$

where $A(\infty) = A_b f_S / (r_0 - f_S \Delta_S)$ is the equilibrium steady-state phase-space area. The phase-space area evolution for zero dilution is presented in Figure 3.4.5.

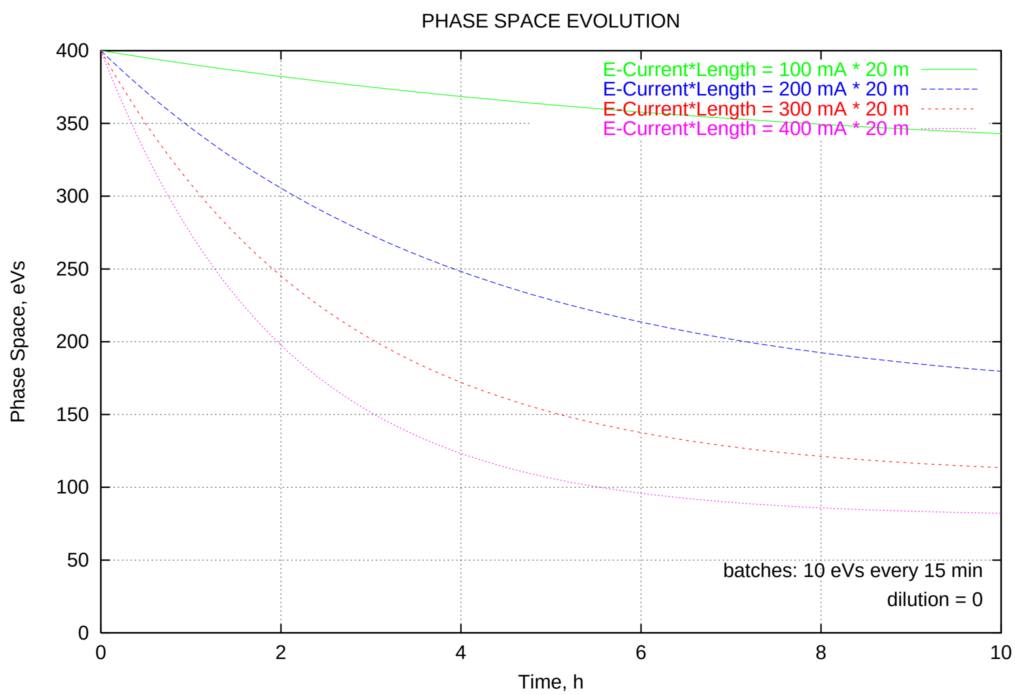

Figure 3.4.5 *Evolution of the longitudinal phase-space area in the cooling-stacking process with zero dilution.*

The sensitivity of the total cooling-stacking time to the dilution value is presented in Figure 3.4.6. The conclusion is that for the injection frequency, f_S, of 4 h^{-1} and the dilution $\Delta_S < 1\%$, the electron current of 300 mA is sufficient for the antiproton accumulation scenario as outlined at the beginning of this section. A description of the stacking process, capable of achieving such small dilutions is presented in Ref. [36]. This stacking process has not been tested yet.

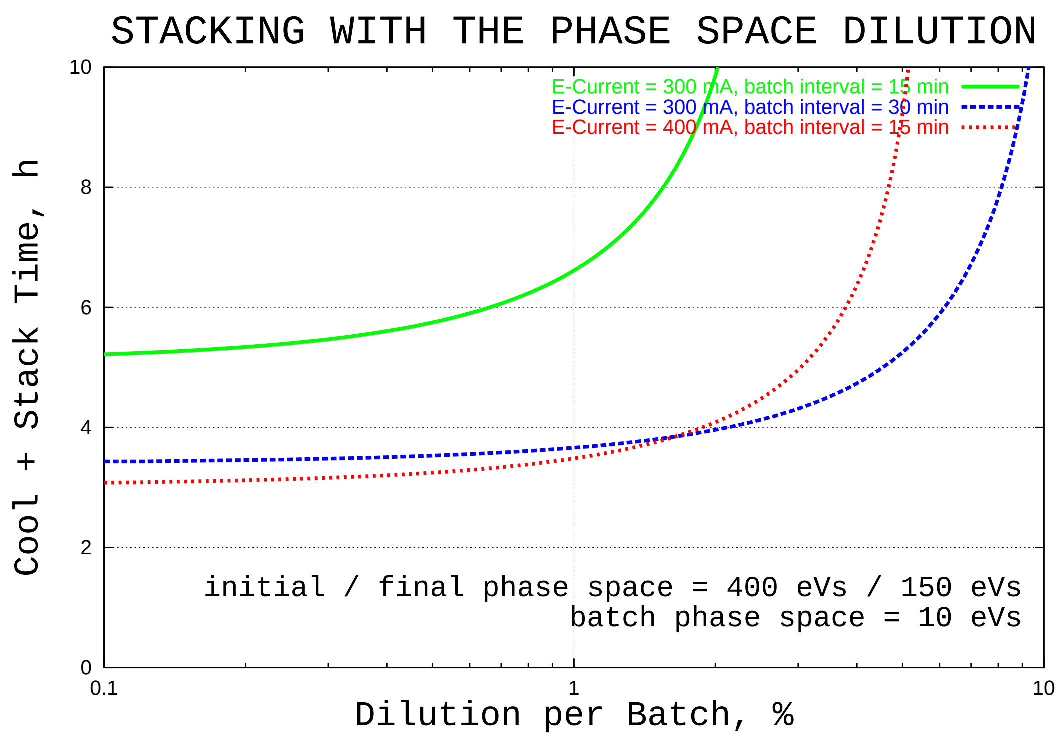

Figure 3.4.6 *Time required to reduce the longitudinal phase-space area from the initial 400 eVs to the final 150 eVs as a function of the dilution parameter, Δ_S. Various curves correspond to various electron currents and/or injection intervals.*

3.4.5 Electron cooling R&D goals

Table 3.4.1 summarizes the important parameters of the Recycler electron cooling system.

The primary technical problem is to generate a high-quality, stable, monochromatic, dc, 4.3-MeV electron beam of 300 mA or greater. The technical goal set in 1995 for an initial proof-of-principal demonstration using mostly existing equipment was to maintain a 200 mA beam for a period of one hour. The only technically feasible way to attain such high electron currents is through beam re-circulation (energy recovery).[37] This goal was achieved in 1998 by re-circulating beam currents of 200 mA for periods of up to five hours without a single breakdown.

The demonstration of the Pelletron-based electron beam re-circulation provided the necessary basis for the next step of the electron cooling R&D program, electron beam transport. Traditional low-energy electron cooling devices employ a continuous homogeneous longitudinal magnetic field in the kilogauss range for the beam transport through the cooling region. One of the main reasons is to suppress the transverse velocities arising from the electron beam space charge. In the Recycler system, the space charge effects are much lower because of the higher beam energy. Thus, the longitudinal magnetic field value can be much smaller, allowing for a non-traditional transport scheme. Also, the choice of a standard Pelletron accelerator prohibits us from immersing the electron beam line into a continuous magnetic field. Our transport scheme assumes a homogenous longitudinal magnetic field in the gun, collector, and in the cooling section, but a lumped focusing system in between.

Parameter	**Value**	**Units**
Electrostatic Accelerator		
Terminal Voltage	4.3	MV
Electron Beam Current	0.5	A
Terminal Voltage Ripple	500	V (FWHM)
Cathode Radius	2.5	mm
Gun Solenoid Field	≤ 600	G
Cooling Section		
Length	20	m
Solenoid Field	≤ 150	G
Vacuum Pressure	0.1	nTorr
Electron Beam Radius	6	mm
Electron Beam Divergence	≤ 80	μrad

Table 3.4.1 *Electron Cooling System Parameters*

The cooling rates are extremely sensitive to the angles between the electrons and the antiproton beam. Both coherent and incoherent angles must be smaller than 10^{-4} radians to avoid cooling degradation. To provide zero angular velocity inside the solenoid, the electrons must enter the solenoid with the correct radius and divergence, determined by the Busch theorem. Diagnostics systems needed to measure the beam radius and divergence are described in Ref. [38].

Figure 3.4.1 shows the schematic layout of the Recycler electron cooling system. This system is now being reproduced at the PB-7 (WideBand) fix-target building for the full-scale proof-of-principle test. The principal goals for this test system are:

1. to demonstrate the re-circulation of a 4.3-MeV, 0.5-A electron beam for a period of one hour;
2. to verify that the electron beam quality in the cooling section meets the demands of the electron cooling;
3. to design the system for the final installation in the Recycler.

Even if these goals are fully accomplished, the ultimate test of the system can only be performed in the Recycler by demonstrating cooling of antiprotons.

3.4.6 Project Plan

Although electron cooling is well understood, the Recycler application represents a major step in beam energy, to 8 GeV from less about 0.5 GeV. The step is large enough that the high voltage generator, beam transport, and cooling region all require extension of the state of the art. Therefore, about 1.5 years (as of November, 2001) of research and development activity are likely to precede introduction of any electron cooling equipment into the Recycler.

The R & D phase of the project has the following plan:

1. To develop an optimized system parameter set (finished);

2. To procure and commission a reliable 4.3 MV electrostatic power supply[39];

3. To design and build an electron beam gun, collector and short (10 m) U-bend transport system[39] to sustain a re-circulating current of at least 0.5 A for 1 hour;

4. To design and implement a precise matching from discrete-element beam transport to continuous cooling region solenoid;

5. To design and implement a 20 m cooling section with uniform axial magnetic field with precision such that electron beam transverse angles are $\leq 10^{-4}$;

6. To design and implement magnetic shielding to protect the electron beam against the magnetic fields of the MI/RR tunnel;

7. To design and build beam instrumentation and control to maintain alignment and equal mean velocity of electron and p-bar beams to precision $\leq 10^{-4}$, to measure beam angular spread and position, to determine neutralization, *etc*.;

8. To assemble a full-scale (60 m) beam line, commission it and establish a recirculating beam current of at least 500 mA at 4.3 MeV, sustainable for 24 hours with a duty cycle of no less than 90%;

9. To demonstrate by measurements that the electron beam angles in the cooling section are $\leq 10^{-4}$.

The laboratory developments are now being carried out in the downstream end of the Wideband Lab experimental area at Fermilab. There is sufficient space at Wideband to carry out the development work envisioned for the Recycler cooling project. The hardware aspects of the development program are treated in detail in Ref. [31]. The goal of the development program is cooling-system hardware ready for installation into the Recycler. The remainder of the work constitutes an Accelerator Improvement Project of moderate scale.

The basic tasks are:

1. Architectural design and civil construction of an enclosure for the high voltage generator and an interconnection tunnel to the MI tunnel for the electron beam transport. The work on this task has already started by Fermilab's FESS;

2. Installation of a Recycler lattice insertion for the cooling region. This task is almost finished. The Recycler lattice suitable for the electron cooling system exists. However, some p-bar trim magnets, diagnostics, and vacuum equipment will have to be installed upstream and downstream of the cooling section at the time of the cooler installation;

3. Installation of cooling section and electron beam transport channels;

4. Commissioning of the cooling system.

3.4.7 Current status

Below is a summary of what has been accomplished as of November, 2001.

Pelletron commissioning:

- The 5 MV Pelletron has been installed and commissioned. While filled with SF6 (no vacuum tubes) at 5.5 atm the Pelletron reached more than 6 MV, thus, no HV problems on the gas side are expected;
- Because of the large amount of energy (3 kJ) stored in the HV terminal and its potential for damage, the HV conditioning of vacuum tubes is performed with the help of shorting rods, one 1-MV section at a time. Each section (out of 5) was conditioned separately to 1.2 MV. The Pelletron with tubes was then conditioned to 4.8 MV. The Pelletron design voltage of 5 MV has not been demonstrated yet. The manufacturer will replace the ceramic accelerating tubes to fix the problem;
- Overall, the Pelletron PO is still incomplete due to several outstanding items (voltage, controls, cooling, documentation) that do not meet the performance criteria. The last 10% invoice has not been paid yet.

Re-circulation test (short beam line):

- Successfully bridged a commercial control system, supplied with the Pelletron, with Fermilab's Acnet. The machine is now 100% Acnet compatible and transparent.
- All Pelletron electronics has been protected against sparks (April-July, 2001)
- Replaced mechanical hardware, damaged by sparks, with more robust components.
- Installed several levels of protection against beam-related full-tube HV breakdowns, which normally resulted in a tube de-conditioning (August, 2001).

- Established a procedure for HV conditioning. Established a procedure for steering the beam into collector. Any operator can now reach 100 mA in about one hour from scratch.
- At 3.5 MV, attained the maximum beam current of 350 mA; the stable current of 120 mA.

Beam line elements:

- All beam line elements are ordered and are to be delivered to Fermilab in Jan.-Feb., 2002.
- Vacuum system is being designed and procured.

Cooling section solenoid:

- A major portion of effort went into understanding the measurement sensor performance and making it stable and reproducible. This has now been achieved.
- The compass-based sensor can measure the solenoid transverse field with a relative accuracy of several mG. Absolute precision, determined by an angle between the magnetic axis of the compass and the mirror, is about 20 mG in a 100 G longitudinal field.
- Two prototype 2-m long solenoid modules were produced, installed and measured.
- The quality of measured solenoid prototypes is satisfactory for our purpose. Integrals of transverse fields can be made below 1 G-cm for the solenoid field of 150 G, if corrector currents are in optimum.
- Twelve new solenoid modules have been wound and epoxied by the Technical Division. Two will be ready for installation in December, 2001.
- We are planing to have a shielding coefficient of 5,000. Only two prototypes of this 3-layer design have manufactured but not tested. The remaining shields will be ordered after the shields are tested.

3.4.8 FY2002 schedule and budget

Project Milestone	**Start Date**	**Finish Date**	**Duration**
Commission U-Bend	3/01	12/01	10 months
500 mA, 1 hour (U-bend)		by 12/31/01	
MI-31 building CDR	01/01/02	04/01/02	3 months
Switch Over to Full Beamline	1/02	3/02	3 months
MI-31 bid out		by 04/01/02	
Commission Beamline	3/02	1/03	11 months
Build MI-31 Enclosure	6/02	12/02	7 months
Push-Pipe	8/02	10/02	3 months
(Shutdown MI)	9/02	10/02	1 month

M&S Budget (k$)	
MI-31 FESS (AIP)	1,266
WideBand (R&D) Cooling Section	342
WideBand (R&D) Supply and return lines	546

General	291
Total	2,445

Physicists	Engineers	Technicians	Drafters	Comp. Prof.
Nagaitsev 100%	Leibfritz 100%	Carlson 50%	MS Draft. 100%	Kramper 50%
Shemyakin 100%	Saewert 100%	Nelson 100%		
Crawford 100%	McGee 50%	Kellett 100%		
Warner 100%	RFI Engr. 50%	Frett 25%		
Burov 100%	Tupikov 100%	EE techs. 100%		
Schmidt 50%				
Kroc 50%				
Grad. student 100%				

3.4.9 FY2003 schedule and budget

Project Milestone	**Start Date**	**Finish Date**	**Duration**
500 mA, 1 hour, beam properties		by 01/31/03	
Disassemble @ Wideband	2/03	4/03	3 months
Install Pelletron @ MI-31	3/03	6/03	4 months
Shutdown MI	8/03	11/03	4 months
Install RR Components	8/03	10/03	3 months
Install Transfer line	9/03	11/03	3 months
Commission E-Cool	12/03		

M&S Budget (k$)	
MI-31 FESS (AIP)	1,800
WideBand Clean-up (R&D)	100
MI-31 installation (AIP)	200
General	200
Total	2,300

Physicists	Engineers	Technicians	Drafters	Comp. Prof.
Nagaitsev 100%	Leibfritz 100%	Carlson 50%	MS Draft. 100%	Kramper 50%
Shemyakin 100%	Saewert 100%	Nelson 100%		
Crawford 100%	McGee 50%	Kellett 100%		
Warner 100%	RFI Engr. 50%	Frett 25%		
Burov 100%	Tupikov 100%	EE techs. 100%		
Schmidt 50%				
Kroc 50%				
Grad. student 100%				

	Total	M&S	Labor	Phys.	Eng.	Draft	Tech	CP
FY02	4070	2445	1625	7	4	1	3.75	0.5
FY03	2605	1500	1105	4.75	2.75	0.75	2.5	0.3
FY04	1320	800	520	2.25	1.25	0.25	1.25	0.2
FY05	0	0	0	0	0	0	0	0
Project	7995	4745	3250	14	8	2	7.5	1

Table 3.4.2 *Funding profile for electron cooling project*